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Microwave Power SiC MESFETs and GaN HEMTs

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ABSTRACT

We have fabricated SiC MESFETs with more than 60 watts of output power at 450 MHz from single 21.6mm gate periphery devices (2.9 W/mm) and 27 watts of output power at 3 GHz from single 14.4mm SiC MESFET devices (1.9 W/mm). We have also demonstrated more than 6.7 W/mm CW power from 400 µm GaN/AlGaN HEMT devices for X band (10 GHz) applications. These excellent device performances have been attributed to the improved substrate and epitaxial films quality, optimized device thermal management, and enhanced device fabrication technologies. The substrates and epitaxial films from different sources were compared and some showed significant less SiC substrate micropipes confirmed by X-ray topography and epitaxial defects characterized by optical defect mapping.

INTRODUCTION

Wide bandgap semiconductors, SiC and GaN, have been viewed as highly promising for microwave power generation at UHF, L/S and X bands [1]. The advantages of wide bandgap materials over the conventional Si and GaAs include high breakdown field, high saturation electron velocity, and high thermal conductivity. For SiC Metal Semiconductor Field Effect Transistors (MESFETs), 250 µm-periphery devices have demonstrated a record power density of 5.6 W/mm at 3 GHz [2]. GaN/AlGaN High Electron Mobility Transistors (HEMTs) can offer even higher power performance due to the higher carrier sheet density and saturation velocity of 2DEG compared to SiC, and record power density of 10 W/mm has been demonstrated from 50µm or 150 µm gate periphery devices [3-4]. With the increased device gate periphery, the power performance will be degraded due to the significant device self-heating and trapping effects. The largest SiC MESFETs were 48 mm gate periphery with 80 watts CW power (1.67 W/mm) at 3GHz [2]. For SiC MESFETs operated at lower frequencies, small gate periphery devices were reported [5-6], but no large gate periphery devices have been reported for UHF band applications.

DEVICE FABRICATION

The SiC MESFET process starts with epitaxial SiC layers grown on either semi-insulating or conductive 4H-SiC substrates. The fabrication process includes mesa isolation, ion implantation for source/drain, ohmic metal sputtering and annealing, recess gate etching, overlay metals, e-beam patterned T-shaped gate with 0.5 µm footprint, airbridge crossovers, and backside vias (not applied yet). The devices were fabricated in house at General Electric global research center. The 14.4mm and 21.6 mm gate periphery devices normally have more than 50% yield. The completed device with airbridges is shown in Fig. 1.

The GaN/AlGaN HEMTs process starts with epitaxial GaN and AlGaN layers grown on 4H-

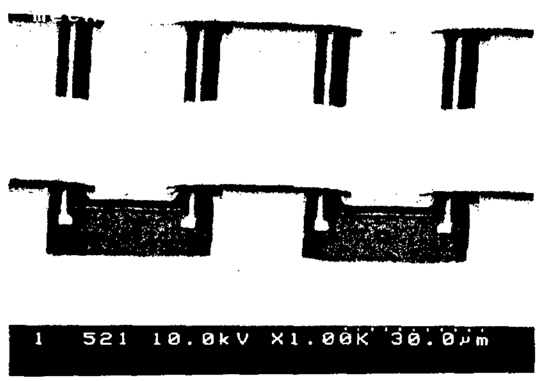

Fig. 1 SiC MESFETs with completed airbridges.

SiC semi-insulating substrates. The fabrication process includes mesa isolation, ohmic metal evaporation and annealing, overlay metals, e-beam patterned T-gate with 0.2~0.3 μm footprint, SiNx surface passivation, airbridge crossovers, and backside vias (not applied yet). The GaN/AlGaN HEMT devices were fabricated in house at General Electric global research center as well.

3-DIMENSIONAL THERMAL SIMULATIONS

For the microwave power devices made from wide bandgap semiconductor materials, the output power can be 5X to 10X more than the conventional microwave power devices made from Si or GaAs. Although SiC substrates offer a thermal conductivity of 4 W/cm·K compared to 1.5 W/cm·K of Si and 0.5 W/cm·K of GaAs, the potentials of device performance will be significantly compromised if the heat dissipation is not properly managed. Wide bandgap semiconductor materials are able to operate at higher temperatures; however, the drain current will be significantly lowered at high temperatures as shown in Fig. 2. For both SiC MESFETs and GaN/AlGaN HEMTs, the full channel current at 300 °C is only about 55% of that at room temperature mainly due to the electron mobility reduction at higher temperatures. To lower

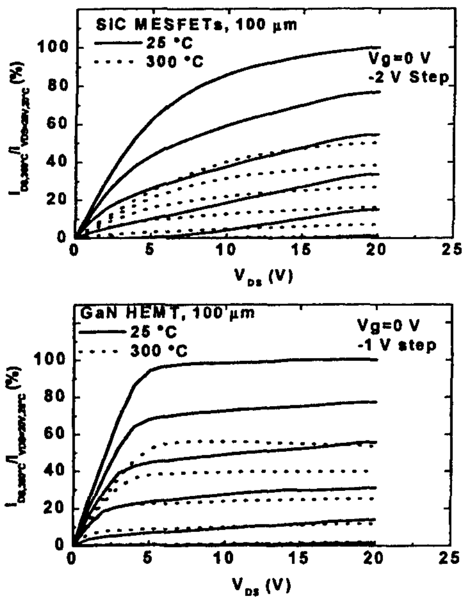

Fig. 2 High temperature DC performance of SiC MESFETs (top) and GaN HEMTs (bottom)

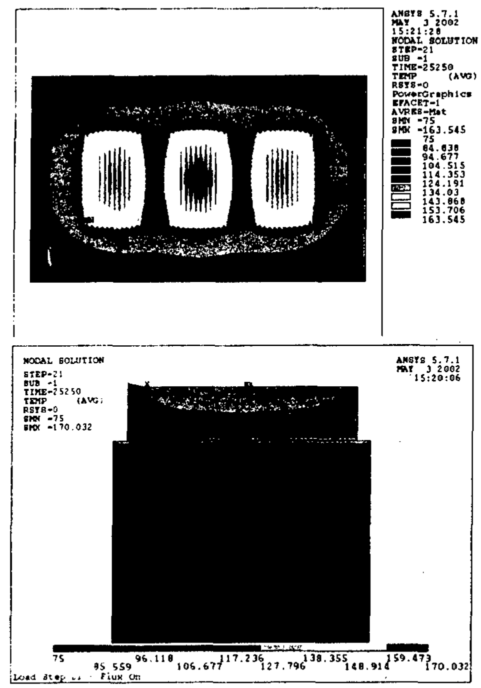

Fig. 3 Three-dimensional thermal simulations: top view (top) and cross-sectional view (bottom).

the junction temperatures, we have developed a 3-dimensional thermal simulation model to optimize the device gate layout designs. Different device gate layouts and package layer buildups were simulated. One example of the simulation results is shown in Fig. 3. The junction temperatures of optimized devices could be lowered by 50~100 °C with negligent phase delays.

SiC MESFETs POWER RESULTS

SiC MESFETs for UHF band applications use either conductive or semi-insulating 4H-SiC substrates. The 21.6 mm gate periphery devices typically have more than 50% yield. The devices were DC screened on-wafer and then diced for packaging. The packaged dies were tested at 450 MHz without matching networks. The power performance from 21.6 mm gate periphery devices is shown in Fig. 4. The devices delivered about 62 watts output power with 1% duty cycle and 250 μs pulse width. This is the highest output power reported for single SiC MESFETs at UHF band. The typical power added efficiency (PAE) was

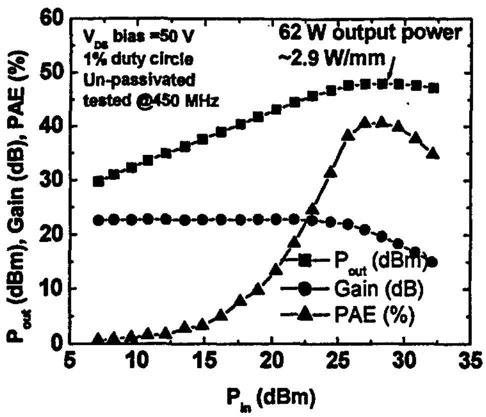

Fig. 4 Power performance of SiC MESFETs at UHF band.

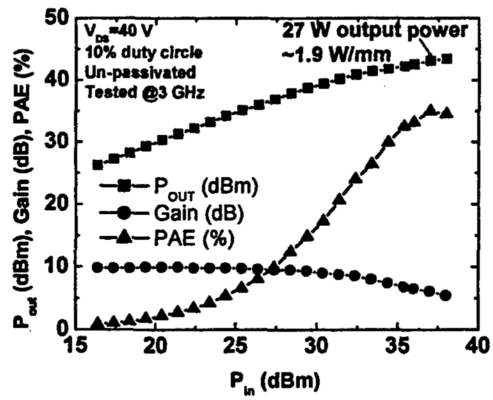

Fig. 5 Power performance of SiC MESFETs at L/S band.

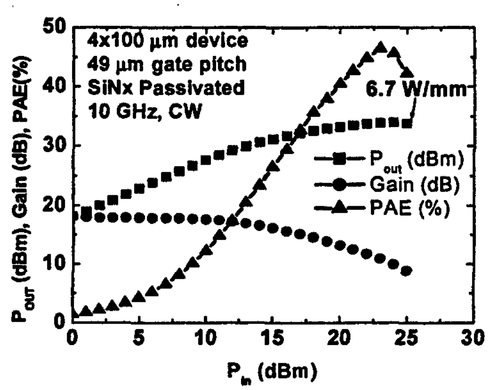

Fig. 6 Power performance of GaN/AlGaN HEMTs at X band.

~40%. The gain was high due to the use of semi insulating substrates. The devices were not passivated and still have the current dispersion effect that will be dealt with later. From the small signal S-parameter measurements, the typical values for frequency response using semi-insulating substrates was ft=7 GHz and fmax=25 GHz and ft=2 GHz and fmax=8 GHz for using conductive substrates (n-type).

Another application window for SiC MESFETs is at L/S band. The devices were fabricated on semi-insulating substrates. The large gate periphery devices were screened on-wafer for DC characteristics using the automated tester. The devices then were diced and packaged. These devices were tested at 3 GHz without matching networks. One typical device power performance is shown in Fig. 5. The device gate periphery was 14.4mm and tested with 10% duty cycle and 250 μs pulsed width at 40 volts drain bias. The total output power was 27 watts which translates to a power density of 1.9 W/mm From the small-signal S-parameters, the values for frequency response were ft=15 GHz and fmax=30 GHz.

GaN/AlGaN HEMTs POWER RESULTS

Due to the superior electron transport properties, such as high mobility, high electrical field and high saturation velocity, GaN/AlGaN high electron mobility transistors (HEMTs) have been the choice for higher frequencies (10 GHz and above) microwave power applications. The unavailability of large bulk GaN crystals has fostered the use of either sapphire or SiC as substrates. Although the highest power density has been obtained from very small gate periphery devices [2-3], the power performance of larger devices has been significantly compromised due to increased junction temperatures and deteriorating defect trapping effects. We have fabricated the devices with gate periphery from 100 μm to more than 10 mm. The power performance of one typical 400 μm gate periphery device on SiC substrates is shown in Fig. 6. The device has 4 gates with 100 μm gate width. The gate pitch was 49 μm to facilitate the good heat dissipation. The gate length was 0.2 μm determined from cross-sectional SEM images. The device was biased at class A with 30 volts drain bias and tested at CW mode at 10 GHz

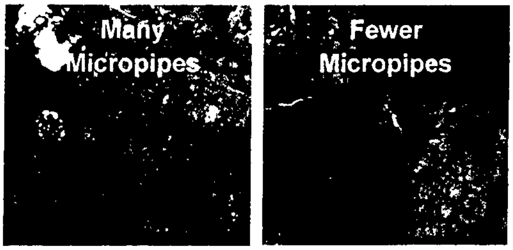

Fig. 7 X-ray topography of SiC semi-insulating substrates.

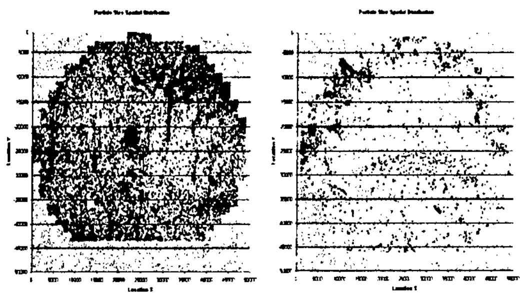

Fig. 8 Optical defect mapping of GaN/AlGaN HEMTs .

without active cooling. The output power density was 6.7 W/mm and power added efficiency was 47%. When the device was biased towards class AB, the PAE increased to more than 57%. The PAE was not pushed to the maximum due to the input power limitations. The large gate periphery devices are being packaged and currently tested.

TRAPPING EFFECTS

The early development of SiC MESFETs and GaN/AlGaN HEMTs has seen very low power densities compared to what can be expected from the DC current-voltage characteristics. This has been attributed to the trapping effects. Traps influence the power performance through the formation of quasi-static charge distributions, most notably on the wafer surface, in the buffer layers underlying the active channel or from the substrates. This parasitic charge acts to limit the drain-current and voltage swings, thereby limiting the high-frequency power output [6-8]. Great efforts have been dedicated to reduce the micropipe density and defects in SiC substrates, to improve the SiC epitaxial film quality, and to improve the epitaxial GaN and AlGaN quality. Surface passivation has

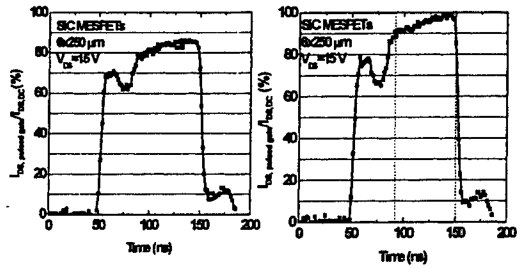

Fig. 9 Pulsed gate I-V characteristics of SiC MESFETs: less trapping (left), more trapping (right).

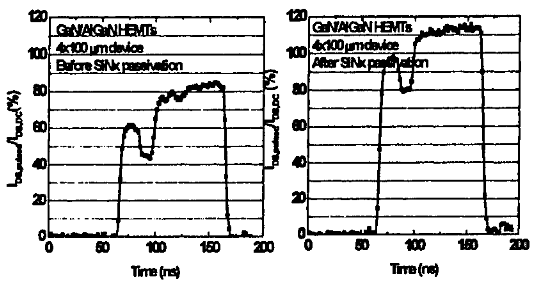

Fig. 10 Pulsed gate I-V characteristics of GaN/AlGaN HEMTs: before passivation (left), after SiNx passivation (right).

also been proven to be critical to stabilize the surface states especially for GaN/AlGaN HEMTs. We used X-ray topography to characterize the micropipes and defects in SiC substrates. Fig. 7 shows the x-ray topography images from two different SiC substrates. One was conventional semi-insulating SiC substrate with Vanadium as compensating doping and another one was Vanadium-free semi-insulating substrate. It is noted that the Vanadium- free substrates have significant fewer micropipes and low angle grain boundaries. Fig. 8 shows the optical defect mapping of GaN/AlGaN HEMTs wafers. The wafer on the right shows significant less defects than the wafer on the left. These micropipes and defects may not only account for the DC to RF current dispersion but also raise the questions for device long-term reliability.

The surface trapping generally can be identified through the gate lag measurements and buffer layer trapping can be characterized by drain lag measurements. Fig. 9 shows gate lag measurements from two SiC MESFET devices. The device gate periphery was 1.5 mm and there is no surface passivation applied. The drain bias was 15 volts while gate baseline was –12 volts. The gate voltage was pulsed from the baseline to +1 volt. The drain current was normalized to the DC drain current under the same conditions. The first device showed significant drain current slump under pulse mode while the devices from another wafer showed less drain current dispersion effects.

Fig. 10 shows the gate lag measurements of GaN/AlGaN HEMTs. The device gate periphery was 400 μm. The drain bias was 15 volts and the gate baseline was –8 volts. The gate was pulsed from the baseline to +1 volt. The drain current was normalized to DC drain current under the same conditions. The device without surface passivation only obtained ~80% of the drain current at DC. In contrast the SiNx passivated devices showed almost no current dispersion. The pulsed drain current over 100% of that at DC under the same condition was due to the reduced DC drain current by device self-heating. These results proved that the surface passivation was effective to stabilize the surface states and therefore almost fully recover the surface trapping effects in GaN/AlGaN HEMTs.

CONCLUSION

SiC MESFETs and GaN/AlGaN HEMTs have been fabricated and characterized. 3-dimensional thermal simulations were critical to fully exploit the device potentials especially for large gate periphery devices. For SiC MESFETs operated at UHF band (450 MHz), 62 watts output power has been obtained from single 21.6 mm gate periphery devices, which is the highest power from single device at UHF band. SiC MESFETs operated at 3 GHz have delivered 27 watts output power from single 14.4 mm gate periphery devices, while GaN/AlGaN HEMTs have demonstrated more than 6.7 W/mm from a 400 μm device tested at 10 GHz. X-ray topography and optical defect mapping have revealed the improvements of micropipes density in SiC semi-insulating substrates and defect density in AlGaN and GaN epitaxial films. Surface passivation on GaN/AlGaN HEMTs showed almost the full recovery of DC drain current dispersion from surface states. The surface passivation is needed for SiC MESFETs to eliminate the surface trapping effects.

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